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Variation in the escape fraction of ionizing photons from galaxies and the redshifted 21-cm power spectrum during reionization

Han-Seek Kim,¹★ J. Stuart B. Wyithe,^{1,2} Jaehong Park¹ and C. G. Lacey³

¹*School of Physics, The University of Melbourne, Parkville, VIC 3010, Australia*

²*ARC Centre of Excellence for All-sky Astrophysics (CAASTRO), Australia*

³*Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*

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ABSTRACT

The observed power spectrum of redshifted 21-cm fluctuations is known to be sensitive to the astrophysical properties of the galaxies that drove reionization. Thus, detailed measurements of the 21-cm power spectrum and its evolution could lead to measurements of the properties of early galaxies that are otherwise inaccessible. In this paper, we study the effect of mass- and redshift-dependent escape fractions of ionizing radiation on the ability of forthcoming experiments to constrain galaxy formation via the redshifted 21-cm power spectrum. We use a model for reionization which combines the hierarchical galaxy formation model GALFORM implemented within the Millennium-II dark matter simulation, with a seminumerical scheme to describe the resulting ionization structure. Using this model we show that the structure and distribution of ionized regions at fixed neutral fraction, and hence the slope and amplitude of the 21-cm power spectrum, are dependent on the variation of ionizing photon escape fraction with galaxy mass and redshift. However, we find that the influence of the unknown escape fraction and its evolution is smaller than the dominant astrophysical effect provided by supernovae feedback strength in high-redshift galaxies. The unknown escape fraction of ionizing radiation from galaxies is therefore unlikely to prevent measurement of the properties of high-redshift star formation using observations of the 21-cm power spectrum.

Key words: galaxies: high-redshift – cosmology: theory – dark ages, reionization, first stars – diffuse radiation.

1 INTRODUCTION

In recent years a great deal of theoretical attention has focused on modelling the effect of galaxies on the reionization of the intergalactic medium (IGM). In large modern simulations, the most common approach is to begin with an N -body simulation to generate a distribution of dark matter haloes (e.g. Ciardi, Stoehr & White 2003; Sokasian et al. 2003; Iliev et al. 2007, 2008; Trac & Cen 2007; Zahn et al. 2007; Shin, Trac & Cen 2008; Trac, Cen & Loeb 2008). A prescription is then used to relate dark matter halo mass to ionizing luminosity. Following this step, radiative transfer methods (most commonly ray-tracing algorithms) are employed to model the generation of ionized structure on large scales. The radiative transfer is normally run with lower resolution than the N -body code for computational efficiency.

An important outcome from the large cosmological volumes attained by modern numerical simulations has been the prediction of 21-cm signals that will be observable using forthcoming low-frequency arrays (e.g. Mellema et al. 2006; Lidz et al. 2008). Lidz

et al. (2008) argue that first generation low-frequency radio telescopes like the Murchison Widefield Array (MWA)¹ and the Low Frequency Array² will have sufficient sensitivity to measure the redshift evolution in the slope and amplitude of the 21-cm power spectrum.³ One of the main limitations in modelling of reionization is the physics of the ionizing sources. Most studies have used very simple prescriptions to assign ionizing luminosities to dark matter haloes. It has been shown that it is then possible to constrain the parameters for these simple prescriptions (e.g. Barkana 2009). However, an important open question is the degree to which the important astrophysics governing formation and evolution of high-redshift galaxies is accessible via observations of the 21-cm power spectrum.

Several studies have previously addressed the issue of realistic modelling of high-redshift galaxies and their role in reionization. For example, Raičević, Theuns & Lacey (2011) (see also

¹ <http://www.haystack.mit.edu/ast/arrays/mwa/>

² <http://www.lofar.org/>

³ We note that MWA has been descaled to 128 elements from the 512 elements used in Lidz et al. (2008).

★ E-mail: hansikk@unimelb.edu.au

Benson et al. 2006; Lacey et al. 2011) used the hierarchical galaxy formation code, *GALFORM* (Cole et al. 2000; Baugh et al. 2005; Bower et al. 2006), implemented within Monte Carlo merger trees to evaluate the ionizing photon budget. They found that although galaxies should produce sufficient ionizing photons to complete reionization, most of the galaxies responsible would be below the detection threshold of current surveys. However, these studies were restricted to global evolution of the ionized fraction, and did not address the ionization structure of the IGM. Most recently, Kim et al. (2013a) have combined the *GALFORM* model implemented within the Millennium-II dark matter simulation with a seminumerical scheme to describe the resulting ionization structure. In this paper we extend this model to consider an escape fraction for ionizing photons that depends on redshift and host halo mass.

The escape fraction of ionizing photons from their host galaxies is one of the most important unknowns for the reionization history. Observational estimates show a broad range of escape fraction values from a few per cent in the local Universe (Hurwitz, Jelinsky & Dixon 1997; Bland-Hawthorn & Maloney 1999; Putman et al. 2003) to a few per cent or a few tens of per cent at redshift $z \sim 1\text{--}3$ (Inoue, Iwata & Deharveng 2006; Shapley et al. 2006; Chen, Prochaska & Gnedin 2007; Siana et al. 2007). However, there are no observational constraints on the escape fraction during the epoch of reionization. Theoretically, the escape fraction is predicted to span a very broad range from 0.01 to 1 (Ricotti & Shull 2000; Wood & Loeb 2000; Benson et al. 2002; Ciardi et al. 2003; Fujita et al. 2003; Sokasian et al. 2003; Wyithe & Loeb 2007; Wise & Cen 2009; Raićević et al. 2011; Kuhlen & Faucher-Giguère 2012).

In this paper we incorporate a variable escape fraction for ionizing photons within the model of Kim et al. (2013a), and predict the redshifted 21-cm power spectrum for the resulting reionization histories. We begin in Sections 2 and 3 by describing the implementation of *GALFORM*, and our method for modelling the ionization structure. Then, in Section 4 we present variant models which lead to different reionization histories, and present a discussion of the dependence of the 21-cm power spectrum on the escape fraction models in Section 5. We finish with some conclusions in Section 6.

2 THE MODEL

In this section we summarize the theoretical galaxy formation modelling based on Kim et al. (2013a) that is used in our analysis in order to describe the new features for this paper.

2.1 The *GALFORM* galaxy formation model

We compute the formation and evolution of galaxy properties using the hierarchical galaxy formation model *GALFORM*. *GALFORM* includes a range of processes that are thought to be important for galaxy formation from dark matter merger histories to baryonic physics such as cooling, star formation, feedback processes and chemical enrichment. A comprehensive overview of *GALFORM* can be found in Cole et al. (2000), with an updated discussion in the review by Baugh (2006). Feedback processes [including active galactic nucleus (AGN), supernovae (SNe) and photoionization] during galaxy formation play very important roles in shaping the luminosity functions predicted by *GALFORM* (Cole et al. 2000; Benson et al. 2002; Baugh et al. 2005; Bower et al. 2006; Kim et al. 2011, 2013b). In this paper, we use the version of *GALFORM* described in Lagos et al. (2012). The Millennium-II Simulation on which the model is based has a cosmology with fractional mass and dark energy densities of $\Omega_m = 0.25$, $\Omega_b = 0.045$ and $\Omega_\Lambda = 0.75$, a dimensionless Hubble

constant of $h = 0.73$ and a power spectrum normalization of $\sigma_8 = 0.9$. The particle mass in the simulation is $6.89 \times 10^6 h^{-1} M_\odot$ and we detect haloes down to 20 particles⁴ in the simulation box of side length $L = 100 h^{-1}$ Mpc (Boylan-Kolchin et al. 2009). Note that our study based on the halo merger trees described in Merson et al. (2013) which are better suited for the purposes of semi-analytic modelling.

2.2 SNe feedback in *GALFORM*

SNe feedback is a dominant physical process in shaping the redshifted 21-cm power spectrum during the reionization (Kim et al. 2013a) owing to its effect on the faint end of the luminosity function. In *GALFORM* SNe reheat gas and eject it from the galaxy disc at a rate

$$\dot{M}_{\text{eject}} = \beta \psi, \quad (1)$$

where ψ is the instantaneous star formation rate and the feedback efficiency β is defined as

$$\beta = (V_{\text{disc}}/V_{\text{hot}})^{-\alpha_{\text{hot}}}. \quad (2)$$

Here V_{hot} and α_{hot} are adjustable parameters to control the SNe feedback strength (cf. Cole et al. 2000) and V_{disc} is the circular velocity of the galactic disc; default values in Lagos et al. (2012) model are $V_{\text{hot}} = 485 \text{ km s}^{-1}$ and $\alpha_{\text{hot}} = 3.2$.

3 SEMI-NUMERICAL SCHEME TO CALCULATE THE EVOLUTION OF THE IONIZED STRUCTURE

Mesinger & Furlanetto (2007) introduced an approximate but efficient method for simulating the reionization process. In this paper we apply a seminumerical technique to find the ionization structure resulting from *GALFORM* galaxies within the Millennium-II dark matter simulation, following the procedure described in Kim et al. (2013a).

We assume the number of photons produced by galaxies within a small volume (or cell) of the simulation, and which enter the IGM to participate in reionization to be

$$N_{\gamma, \text{cell}} = \int_0^{t_z} \dot{N}_{\text{Lyc, cell}}(t) dt. \quad (3)$$

The total Lyman continuum luminosity of the N_{cell} galaxies within the cell expressed as the emission rate of ionizing photons (i.e. units of photons s^{-1}) is

$$\dot{N}_{\text{Lyc, cell}}(t) = \sum_{i=1}^{N_{\text{cell}}} \dot{N}_{\text{Lyc, } i}(t), \quad (4)$$

where

$$\dot{N}_{\text{Lyc, } i}(t) = f_{\text{esc}} \int_{v_{\text{thresh}}}^{\infty} \frac{L_{v, i}(t)}{h\nu} dv, \quad (5)$$

⁴ A limit of 20 particles might be aggressive. Jenkins et al. (2001) show that the halo mass function agrees well down to haloes including only 20 particles although this is for halo masses $\sim 10^{12} h^{-1} M_\odot$ and $z = 0$. Reed et al. (2007) show that the number of particles needed for accurate convergence of the halo mass function of high redshift $z = 10\text{--}30$ and halo masses $10^5\text{--}10^7 h^{-1} M_\odot$ is 100 particles. However, since the errors less than 20 per cent the 20 particle limit should not have a significant effect on our conclusions.

where f_{esc} is the escape fraction of ionizing photons produced by stars in a galaxy. $L_{\nu,i}$ is the spectral energy distribution of galaxy i and ν_{thresh} is the Lyman-limit frequency ($h\nu_{\text{thresh}} = 13.6$ eV). Note that the number of photons produced per baryon in long-lived stars and stellar remnants depends on the initial mass function (IMF) and metallicity (Z). This number is calculated self-consistently in GALFORM. We use the Bruzual & Charlot models (Bruzual & Charlot 1993, 2003). The stellar population models used give 4.12×10^3 for $Z = 0.02$ and 6.20×10^3 for $Z = 0.004$ using a Kennicutt IMF. We assume the total Lyman continuum luminosity in a cell at redshift z_i to be constant until the next snapshot at redshift z_{i+1} , and calculate the number of photons produced in the cell between z_i and z_{i+1} as $\dot{N}_{\text{Lyc,cell}}(t_{z_i})(t_{z_{i+1}} - t_{z_i})$.

We then calculate the ionization fraction within each cell accordingly

$$Q_{\text{cell}} = \left[\frac{N_{\gamma,\text{cell}}}{(1 + F_c)N_{\text{H I,cell}}} \right], \quad (6)$$

where F_c denotes the mean number of recombinations per hydrogen atom up to reionization and $N_{\text{H I,cell}}$ is the number of neutral hydrogen atoms within a cell. The latter quantity is calculated as

$$N_{\text{H I,cell}} = \bar{n}_{\text{H I}}(\delta_{\text{DM,cell}} + 1)V_{\text{cell}}, \quad (7)$$

where we assume that the overdensity of neutral hydrogen follows the dark matter (computed based on the Millennium-II Simulation density field), $\bar{n}_{\text{H I}}$ is the mean comoving number density of hydrogen atoms and V_{cell} is the comoving volume of the cell. Self-reionization of a cell occurs when $Q_{\text{cell}} > 1$. We divide the Millennium-II Simulation box into 256^3 cells, yielding cell side lengths of $0.3906 h^{-1}$ Mpc and comoving volumes of $0.0596 h^{-3}$ Mpc³.

Theoretical prediction of the parameters F_c and f_{esc} in equations (3) and (6) from first principles is complicated, and their values are not known. The recombination parameter F_c is related to the density of the IGM on small scales, while f_{esc} depends on the details of the high-redshift interstellar medium (ISM). Previous work using GALFORM suggested the value $(1 + F_c)/f_{\text{esc}} \sim 10$ (Benson et al. 2001; Raićević et al. 2011; Kim et al. 2013a) to fit observational constraints on reionization. Here, we vary the value of f_{esc} , assuming $F_c = 0.5$, as a function of redshift or host dark matter halo mass to see the effect of different histories of reionization on the 21-cm power spectrum.

Based on equation (6), individual cells can have $Q_{\text{cell}} > 1$. On the other hand, cells with $Q_{\text{cell}} < 1$ may be ionized by photons produced in a neighbouring cell. In order to find the extent of ionized regions we therefore filter the Q_{cell} field using a sequence of real space top hat filters of radius R (with $0.3906 < R < 100 h^{-1}$ Mpc), producing one smoothed ionization field Q_R per radius.⁵ At each point in the simulation box we find the largest R for which the filtered ionization field is greater than unity (i.e. ionized with $Q_R > 1$). All points within the radius R around this point are considered ionized. This procedure forms the position-dependent ionization fraction $0 \leq Q \leq 1$, which describes the ionization structure of the IGM during reionization.

In this paper we restrict our attention to analyses that assume the spin temperature of hydrogen is coupled to the kinetic temperature of an IGM that has been heated well above the cosmic microwave

background (CMB) temperature (i.e. $T_s \gg T_{\text{CMB}}$). This condition should hold during the later stages of the reionization era ($z \lesssim 9$; Santos et al. 2008). In this regime there is a proportionality between the ionization fraction and 21-cm intensity, and the 21-cm brightness temperature contrast may be written as

$$\Delta T(z) = T_0(z)[1 - Q](1 + \delta_{\text{DM,cell}}), \quad (8)$$

where $T_0(z) = 23.8 \left(\frac{1+z}{10}\right)^{1/2}$ mK. We have ignored the contribution to the amplitude from velocity gradients, and assumed as before that the hydrogen overdensity follows the dark matter ($\delta_{\text{DM,cell}}$).

4 MODELLING THE REIONIZATION HISTORY

In this paper, we assume several different models for f_{esc} as defined in Section 3. Specifically we model dependencies of the escape fraction with halo mass and redshift using

$$f_{\text{esc}} = A \left(\frac{1+z}{7} \right)^\alpha (\log_{10}(M_{\text{halo}}/h^{-1} \text{M}_\odot)/10)^\beta, \quad (9)$$

where A is normalization parameter, α describes the redshift dependence and β describes the halo mass dependence. We force to $f_{\text{esc}} = 0$ when the value of equation (9) is negative and $f_{\text{esc}} = 1$ when the value is greater than unity. We also consider a fiducial model with $f_{\text{esc}} = \text{constant}$. We assume F_c to equal 0.5 (Barkana & Loeb 2001; Furlanetto & Oh 2005). We note that F_c may vary with environment. However, as shown in Wyithe & Morales (2007), clumping of gas is secondary to the bias of ionizing sources in terms of 21-cm fluctuation amplitude. We therefore choose a constant value of F_c for the models presented in this paper. To facilitate comparison, we assume that A is normalized so that the ionization fraction at $z = 7.272$ is $\langle x_i \rangle = 0.5$ for all models. In Table 1, we show the parameters describing the eight models used in this paper. These models are discussed below.

4.1 Redshift dependence modelling

There is uncertainty in the redshift dependence of the escape fraction of ionizing photons (Inoue et al. 2006; Shapley et al. 2006; Siana et al. 2010; Kuhlen & Faucher-Giguère 2012). Here, we model the effect of a redshift dependence of the escape fraction, f_{esc} , on the evolution of the mass averaged ionization fraction using three different redshift dependences.

SN-0: f_{esc} is constant with redshift.

SN-I: f_{esc} increases with redshift.

SN-II: f_{esc} decreases with redshift.

Table 1. The values of selected parameters which are different in the models. The columns are as follows: (1) whether the model with or without SNe feedback; (2) the name of the model; (3) normalization value to match $\langle x_i \rangle = 0.5$ at $z = 7.272$; (4) index α describing redshift dependence; (5) index β describing halo mass dependence.

With or without SNe feedback	Name	A	α	β
With	SN-0	0.5348	0	0
With	SN-I	0.1488	5	0
With	SN-II	1.6791	-5	0
With	SN-III	0.3649	0	5
With	SN-IV	0.7358	0	-5
Without	NOSN-0	0.0319	0	0
Without	NOSN-III	0.0456	0	5
Without	NOSN-IV	0.0201	0	-5

⁵ Zahn et al. (2011) have shown that a sharp k -space filter provides a better correlation of density and ionization than using a real-space top-hat filter, though the differences are small and will not affect the comparisons that are the focus of this work.

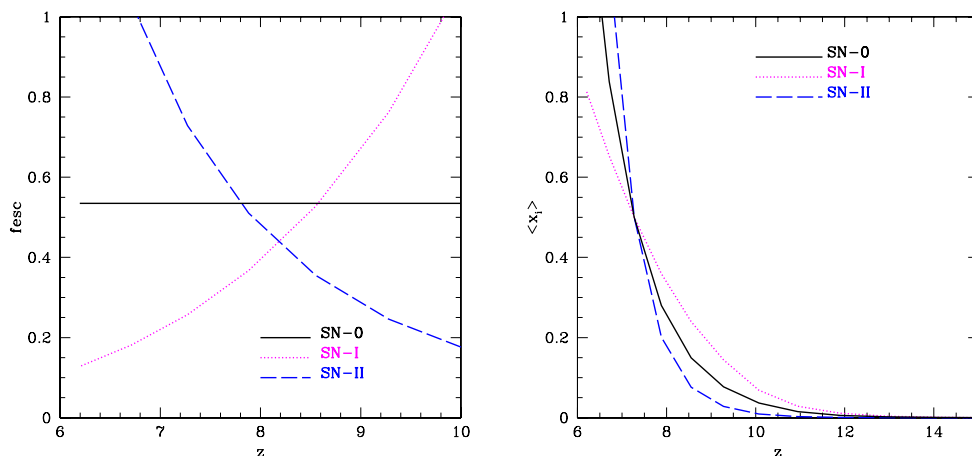


Figure 1. Left: the evolution of f_{esc} as a function of redshift for the three redshift-dependent models SN-0, SN-I and SN-II. Right: the evolution of the mass averaged ionization fraction evolution for the models SN-0, SN-I and SN-II.

For our fiducial GALFORM model with SNe feedback, Fig. 1 shows the assumed redshift evolution of f_{esc} (left-hand panel), together with the resulting mass averaged ionization fraction ($\langle x_i \rangle$) from the different models (right-hand panel). SN-II completes reionization earlier than the other two models, and has the fastest evolution. On the other hand, SN-I completes reionization later than other two models and has the slowest evolution.

4.2 Halo mass dependence modelling

It is unknown whether the escape fraction of photons has a dependence on host halo mass (Gnedin, Kravtsov & Chen 2008; Wise & Cen 2009; Razoumov & Sommer-Larsen 2010; Yajima, Choi & Nagamine 2011). Here we model the effect of a host halo mass dependence of escape fraction on the evolution of the mass averaged ionization fraction using two different assumptions for the host dark matter halo mass dependence.

SN-III: f_{esc} increases with halo mass.

SN-IV: f_{esc} decreases with halo mass.

For our fiducial GALFORM model with SNe feedback, Fig. 2 shows the assumed dependence of f_{esc} on host dark matter halo mass (left-hand panel) and the evolution of the resulting mass averaged ionization fractions ($\langle x_i \rangle$). SN-III and SN-IV show similar evolution of

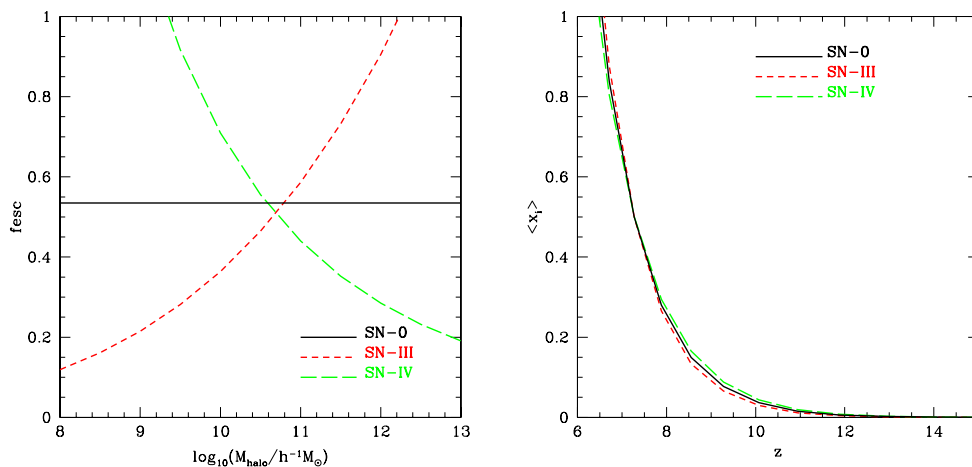


Figure 2. Left: the values of f_{esc} as a function of host dark matter halo mass for two halo-dependent models SN-III and SN-IV. Right: the evolution of the mass averaged ionization fraction for the two models SN-III and SN-IV.

ionization fraction. This is because the ionizations are dominated by galaxies near $10^{10} h^{-1} M_{\odot}$, above which galaxies are rare, and below which flux is suppressed by feedback processes (see also Fig. 4). The difference between the ionization fraction evolution histories of the host halo mass dependent models is smaller than for the redshift-dependent models in Fig. 1.

4.3 Modelling without supernovae feedback

The importance of SNe feedback during reionization is not constrained by current observations. We therefore investigate the halo-dependent modelling of f_{esc} in GALFORM models without SNe feedback. Note that we have not considered redshift-dependent modelling of the escape fraction in models without SNe feedback.

NOSN-0: f_{esc} is constant with redshift.

NOSN-III: f_{esc} increases with halo mass.

NOSN-IV: f_{esc} decreases with halo mass.

As before we adjust the normalization value produce $\langle x_i \rangle = 0.5$ at $z = 7.272$ for all models. Note that the required f_{esc} is much lower in the NOSN models due to the much larger contribution from low-mass haloes than SN models.

Fig. 3 shows the assumed dependence of f_{esc} on host dark matter halo mass (left-hand panel) and the evolution of the resulting mass

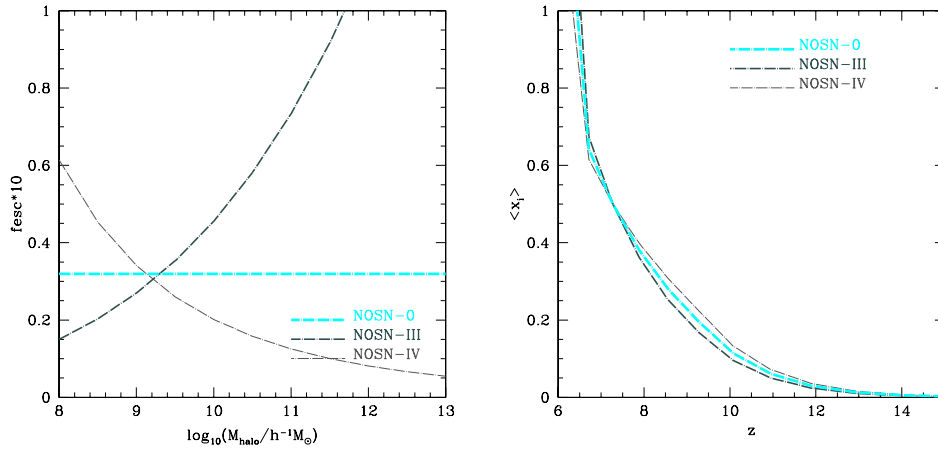


Figure 3. Left: the values of f_{esc} as a function of host dark matter halo mass for three halo-dependent NOSN-0, NOSN-III and NOSN-IV. Right: the evolution of the mass averaged ionization fraction for the three models.

averaged ionization fractions ($\langle x_i \rangle$) for models without SNe feedback. NOSN-0, NOSN-III and NOSN-IV in Fig. 3 show a slightly larger difference between models than SN-III and SN-IV (Fig. 2) in the evolution of ionization fraction. This implies that with respect to the evolution of mass averaged ionization fraction ($\langle x_i \rangle$), the halo-mass-dependent escape fraction has a more significant effect in models without SNe feedback. However, the difference between the ionization fraction evolution histories of the host halo mass dependent models is smaller than for the redshift-dependent f_{esc} models in cases both with and without SNe feedback.

Fig. 4 shows the cumulate fraction of the contribution to the emission rate of ionizing photons as a function of halo masses for models SN-0 and NOSN-0 at $\langle x_i \rangle = 0.5$. The dominant halo mass range contributing the ionizing photons in SN-0 model is greater than in NOSN-0 model (see also Raičević et al. 2011). The halo mass below which 50 per cent is produced of the total emission rate of ionizing photons is $\sim 10^{9.4} h^{-1} M_\odot$ for the NOSN-I model and $\sim 10^{10.9} h^{-1} M_\odot$ for the SN-I model.

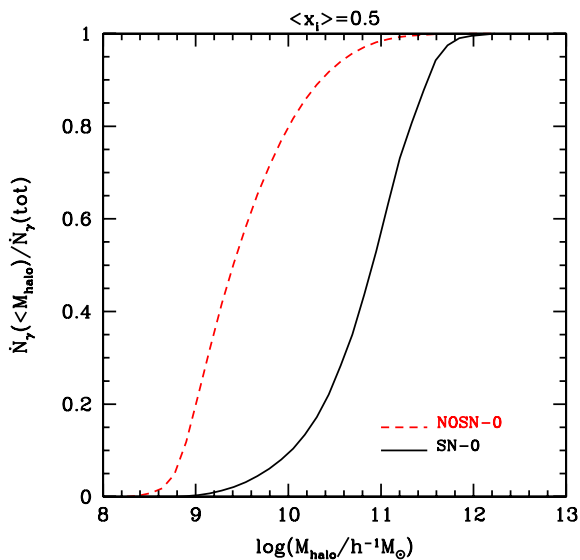


Figure 4. The cumulative fraction of contribution to the emission rate of ionizing photons as a function of halo masses for models SN-0 and NOSN-0 at $\langle x_i \rangle = 0.5$.

5 THE 21-cm POWER SPECTRUM

The filtering procedure described in Section 3 provides three-dimensional maps of the ionization structure and 21-cm intensity within the Millennium-II Simulation box. From this cube we calculate the dimensionless 21-cm power spectrum,

$$\Delta^2(k) = k^3 / (2\pi^2) P_{21}(k, z) / T_0(z)^2, \quad (10)$$

as a function of spatial frequency k , where $P_{21}(k)$ is the three-dimensional power spectrum of 21-cm brightness temperature $\Delta T(z)$ (described by equation 8).

Fig. 5 shows the evolution of the predicted dimensionless 21-cm power spectra for SN-0–SN-IV and NOSN-0 models. The predicted power spectra show different amplitudes and shapes at the same redshift partly because each model has reached a different stage of reionization, and partly because of the relative fraction of ionizing photons emitted from large versus small galaxies.

Lidz et al. (2008) demonstrated that first generation low-frequency arrays like the MWA⁶ should have sufficient sensitivity to measure the amplitude and slope of the 21-cm power spectrum. To quantify the effect of assuming an f_{esc} that depends on redshift or host dark matter halo mass we therefore compare the amplitude and slope of predicted 21-cm power spectra for different models. In Fig. 6, we plot these values as a function of $\langle x_i \rangle$ for central wave numbers corresponding to the point on the power spectrum at which we evaluate the amplitude and gradient. We choose results for $k_p = 0.2$ and $0.4 h^{-1} \text{ Mpc}$, corresponding to the range of wave numbers to be probed by the MWA. We plot both redshift-dependent (left-hand panel) and host dark matter halo mass dependent (middle panel) cases using the fiducial GALFORM model with SNe feedback, as well as the host dark matter halo mass dependent f_{esc} model without SNe feedback (right-hand panel). We also include an error bar which shows the calculated fractional uncertainty in the power spectrum:

$$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\text{modes}}}}, \quad (11)$$

where the n_{modes} is the number of Fourier modes present in a spherical shell of width δk within volume of V . For large scales, $k \ll 2\pi/V^{1/3}$, and $n_{\text{modes}} = V 4\pi\delta k / (2\pi)^3$ (Feldman, Kaiser & Peacock 1994; Angulo et al. 2008). We note that this error is a

⁶ www.mwa.org

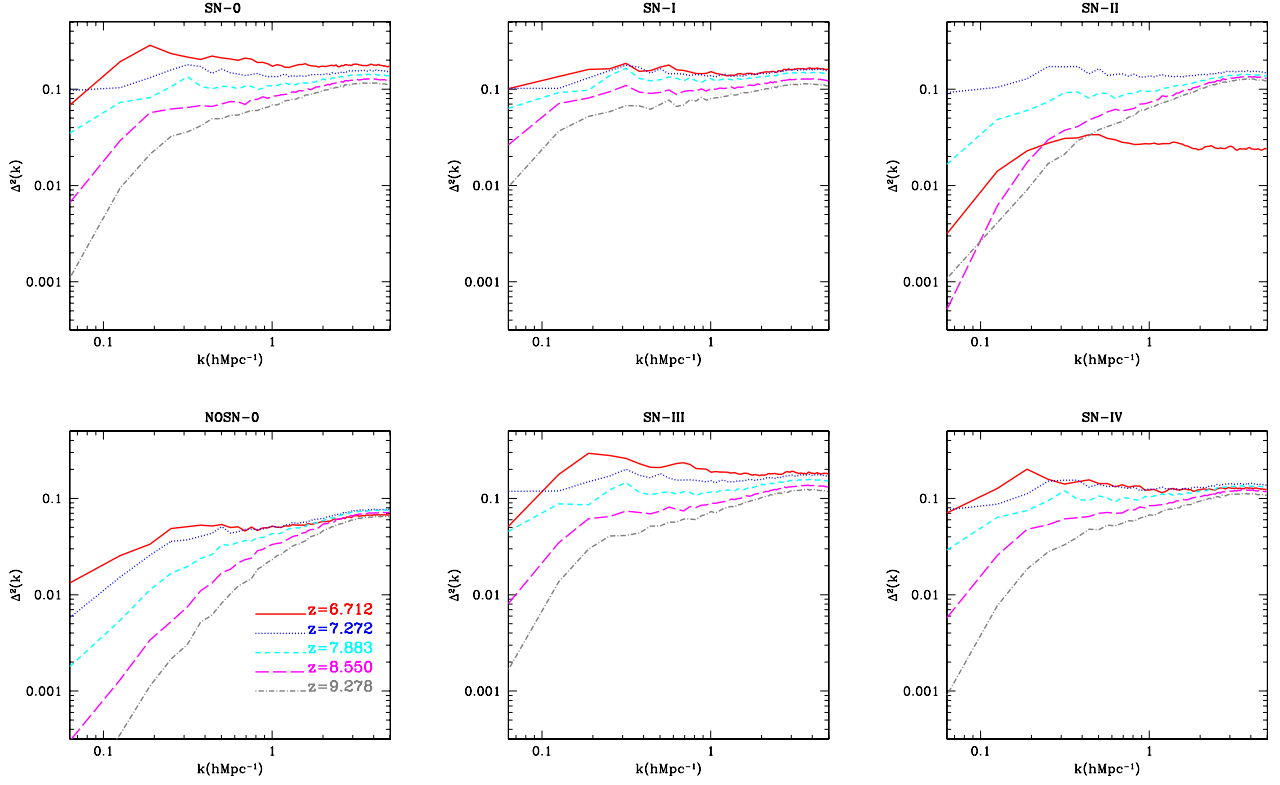


Figure 5. The evolution of the predicted 21-cm dimensionless power spectra. Colours and line styles show different redshifts as shown by the key.

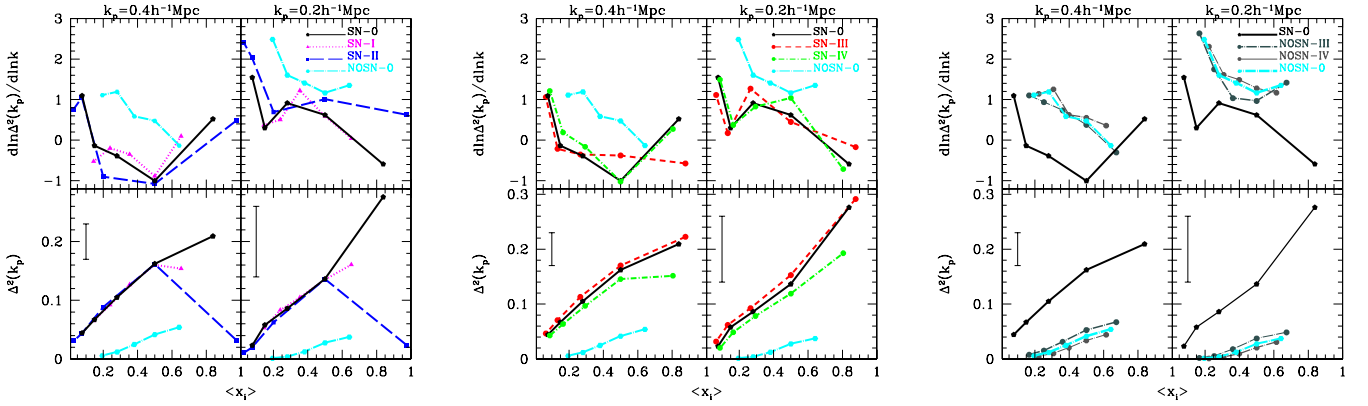


Figure 6. Plots of the evolution in dimensionless 21-cm power spectrum amplitude (lower panels) and slope (upper panels) as a function of ionization fraction $\langle x_i \rangle$. Predictions are shown for redshift-dependent f_{esc} models (left-hand panel), halo-mass-dependent f_{esc} models with SNe feedback (middle panel) and halo-mass-dependent f_{esc} models without SNe feedback (right-hand panel). Results are shown for two central wavenumbers, $k_p = 0.4$ (left) and $0.2 h^{-1} \text{ Mpc}$ (right) in each case, corresponding to the point on the power spectrum at which we evaluate the amplitude and gradient. The error bars in the lower panels show the fractional error in the measured power spectrum owing to finite volume.

statistical error of the simulation, whereas the different models have been computed on the same density field. The error therefore overestimates the uncertainty in the difference between models.

Interestingly, models SN-0–SN-IV which describe variation of f_{esc} with host halo mass and redshift do not show significant variation in either amplitude or slope of 21-cm power spectrum. Similarly, the cases with halo-mass-dependent f_{esc} models and GALFORM without SNe feedback (NOSN-III and NOSN-IV) show only small differences from the NOSN model with constant f_{esc} . However, all models without SNe feedback (NOSN-0, NOSN-III and NOSN-IV) show significant differences across a range of ionization fraction when compared to GALFORM models with SNe feedback included

(SN-0–SN-IV). In particular, the power spectrum amplitudes of models without SNe feedback are lower than for models SN-0–SN-IV with SNe feedback. The amplitude of the 21-cm power spectrum on large scales is sensitive to the bias of ionizing source during the reionization (McQuinn et al. 2007). The difference in amplitude between models with SNe feedback (SN-0–SN-IV) and without SNe feedback (NOSN-0, NOSN-III and NOSN-IV) illustrates the different contribution to ionization from low-mass, low-bias galaxies. The dominant galaxies driving reionization in models with SNe feedback are big galaxies within large haloes. However, the contribution of small galaxies in models without SNe feedback is much larger than in models with SNe feedback.

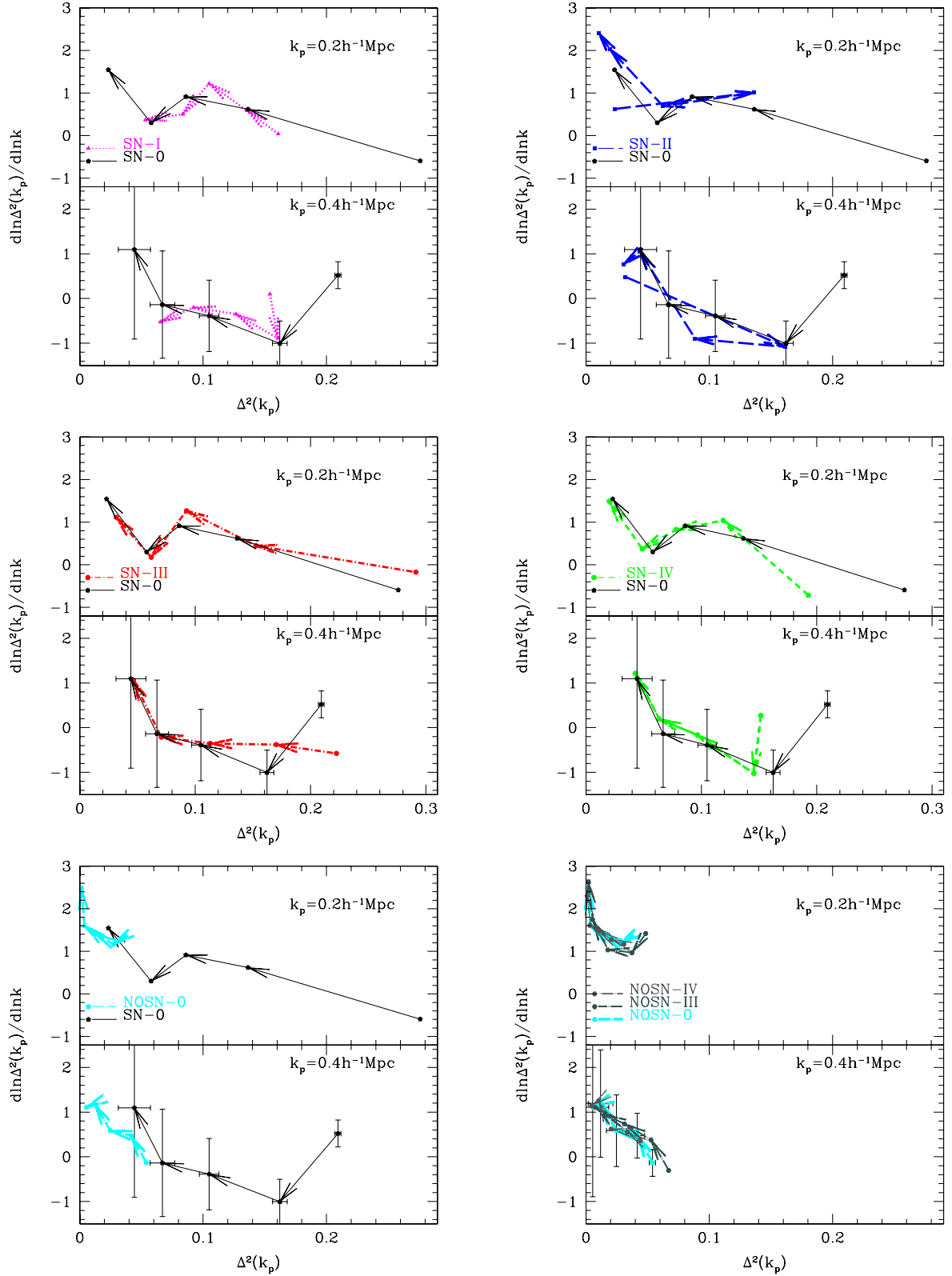


Figure 7. Plots of the loci of points in the parameter space of 21-cm power spectrum amplitude and slope. Loci are shown for each of redshift-dependent f_{esc} models SN-I and SN-II (top panels), halo-mass-dependent models SN-III and SN-IV (middle panels) and NOSN-0 model (bottom left-hand panel) with the SN-0 prediction plotted for comparison in each panel. Loci are shown in the bottom right-hand panel for halo-mass-dependent models without SNe feedback NOSN-0, NOSN-III and NOSN-IV. Results are shown for two central wavenumbers, $k_p = 0.2$ (top of each panel) and $0.4 h^{-1} \text{ Mpc}$ (bottom of each panel), corresponding to the point on the power spectrum at which we evaluate the amplitude and gradient. The error bars for $0.4 h^{-1} \text{ Mpc}$ at each point on the Model 0 correspond to estimates for the MWA (Lidz et al. 2008) with 1000 h of integration and 6 MHz of bandpass.

5.1 Observational implications

Since the ionization fraction is not a direct observable, we also plot the progression of a model in the observable plane of power spectrum amplitude versus slope. These are shown for models with SNe feedback (SN-0–SN-IV) and without SNe feedback (NOSN-0, NOSN-III and NOSN-IV) in Fig. 7, again for the two values of central wavenumber k_p . The arrows show the direction from high to low $\langle x_i \rangle$. To illustrate the potential for detectability of this difference we also include error bars for wavenumber $k_p = 0.4 h^{-1} \text{Mpc}$ corresponding to estimates for the MWA (specifically an r^{-2} distribution of 500 antennas; Lidz et al. 2008) assuming 1000 h integration and 6-MHz bandpasses. We note that MWA has been descope to 128 antennas, and is unlikely to make detailed Epoch of Reionization (EoR) measurements (Bowman et al. 2013). We present errors for 512 antennas which represents an upgrade of the MWA.

Fig. 7 compares models with SNe feedback (SN-I–SN-IV) and without SNe feedback (NOSN-0, NOSN-III and NOSN-IV) to SN-0 (which has constant f_{esc}). As noted in the previous section, we find that the effect of SNe feedback strength has a much larger influence on the evolution of ionization structure during the EoR than the different dependencies of escape fractions on redshift or host dark matter halo mass considered in this paper. All models without SNe feedback produce curves in the $\Delta^2(k) - d \ln \Delta^2(k) / d \ln k$ plane that lie at lower values of $\Delta^2(k)$. Observation of a large $\Delta^2(k)$ would therefore imply the presence of SNe feedback (or other mechanism which raises the bias of ionizing sources), irrespective of the dependence on ionization fraction within the range of models considered. Kim et al. (2013a) demonstrated that other astrophysical effects including the IMF and star formation law have a smaller effect on the 21-cm power spectrum. As a result these will be much more difficult to separate from the effects of unknown escape fraction.

6 CONCLUSION

Over the next decade we are likely to see the first measurements of the power spectrum of redshifted 21-cm fluctuations from neutral hydrogen structure during the EoR. One goal of these experiments will be to learn about the properties of the galaxies that drove the reionization process. It is known that the ionization structure of the IGM, and hence the observed 21-cm power spectrum, will be sensitive to the astrophysical properties of the reionizing galaxies. In this paper we have extended the semi-analytic model for reionization presented in Kim et al. (2013a) to include the possibility of redshift- or mass-dependent escape fractions. This model combines the GALFORM galaxy formation model implemented within the Millennium-II dark matter simulation with a seminumerical scheme to describe the resulting ionization structure. We find that an escape fraction which varies with galaxy mass and redshift influences the structure of reionization. However, we find that the effect is smaller than the dominant astrophysical influence of SNe feedback. Thus, we conclude that the unknown dependence on the escape fraction will not influence the ability of observations to determine the dominant physics of galaxy formation during reionization from the observed 21-cm power spectrum.

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